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A Social-aware Group Formation Framework for Information Diffusion in Narrowband Internet of Things

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***Abstract*—Due to the heterogeneous and resource-constrained characters of Internet of Things (IoTs), how to guarantee ubiquitous network connectivity is challenging. Although LTE cellular technology is the most promising solution to provide network connectivity in IoTs, information diffusion by cellular network not only occupies its saturating bandwidth, but also costs additional fees. Recently, NarrowBand-IoT (NB-IoT), introduced by 3GPP, is designed for low-power massive devices, which intends to re-farm wireless spectrum and increase network coverage. For the sake of providing high link connectivity and capacity, we stimulate effective cooperations among User Equipments (UEs), and propose a Social-Aware Group formAtion framework (named as SAGA) to allocate Resource Blocks (RBs) effectively following an in-band NB-IoT solution. Specifically, we first introduce a social-aware multihop Device-to-Device (D2D) communication scheme to upload information toward the eNodeB within a LTE, so that a logical cooperative D2D topology can be established. Then, we formulate the D2D group formation as a scheduling optimization problem for RB allocation, which selects the feasible partition for the UEs by jointly considering relay method selection and spectrum reuse for NB-IoTs. Since the formulated optimization problem has a high computational complexity, we design a novel heuristic with a comprehensive consideration of power control and relay selection. Performance evaluations based on synthetic and real trace simulations manifest that the presented method can significantly increase link connectivity, link capacity, network throughput and energy efficiency comparing with the existing solutions.**

***Index Terms*—NB-IoTs, group formation, D2D communications, social selfishness, relay selection, power control.**

I. Introduction

Billions of devices in Internet of Things (IoTs) with sensing, computing, and communication capabilities are facilitating our daily life from various aspects, such as environmental monitoring, health care, product management, and smart cities [1]. According to the mobility report from Ericsson[1], mobile traffic will reach more than 120 exabytes per month in 2018, which is about 12 times comparing with the counterpart in 2012. The rapid growth of traffic challenges the current communication infrastructure, especially in urban areas and at peak periods [2]. Since devices in IoTs would be interconnected by heterogeneous network architectures, how to guarantee network connectivity is a fundamental issue. Due to the various advantages of LTE cellular technology (such as wide coverage, security, and licensed spectrum), it is a promising alternative to offer network connectivity in IoTs. However, global cellular traffic has reached 94 exabytes in 2015, and it is estimated to reach around 910 exabytes per month in 2020 [3]. Therefore, the increasingly scarce spectrum resource and additional cost fees have become the obstacles for the implementation of LTE cellular technology in IoTs [4].

In order to enable machine-type communications in 5G, novel technology components, such as NarrowBand-IoT (NB-IoT) radio interface, D2D communications, and licensed assisted access are advocated by 3GPP. NB-IoT technology, included in 3GPP LTE-standard Release 13, has been demonstrated to effectively reduce the required time of specific applications in LTE by reusing network resources, such as downlink Orthogonal Frequency Division Multiple Access (OFDMA), channel coding, and so forth [5]. NB-IoT is initially designed to coexist with the 3GPP devices, and can be deployed by LTE operators through allocating physical Resource Blocks (RBs) of 180 kHz [6]. In September 2015, the normative phase of the NB-IoT work item in 3GPP has launched, and the core specifications have been accomplished in June 2016.

In IoTs, each thing or person with a locatable, addressable, and readable counterpart can be connected, and objects can collaborate with each other toward the same goal [7]. The evolutionary direction of IoTs is changing from smart objects to social objects, which calls for the comprehensive management of interaction among Device-to-Device (D2D), Device-to-Infrastructure (D2I), and Device-to-Human (D2H) [8]. D2D communications between User Equipments (UEs) within mutual proximity are promising to offload the ever-saturating bandwidth of cellular networks, increase spectrum utilization and provide high network throughput [9]. Existing communication techniques (such as radio frequency identification, Zigbee, Bluetooth, and low-power WiFi) are investigated to support D2D communications by unlicensed frequency bands. Although multi-hop D2D communications can be fulfilled to provide wide coverage, additional backhaul links are required and link interruption may also occur. Besides, the utilization of unlicensed spectrum lowers network reliability and availability, and adds communication delay.

As an important branch of IoTs, NB-IoTs can support large number of devices with the characters of low bandwidth, low

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[1]https://www.ericsson.com/assets/local/news/2013/6/ericsson-mobility-report-june-2013.pdf

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device cost, low power consumption and low delay sensitivity [10]. Although commercial applications of NB-IoT products and services have been launched in 2017, how to design a social-aware framework for information diffusion in D2D-enabled NB-IoT is still in its infancy. Furthermore, since cellular network is initially designed for human-to-human communications, additional requirements deserve to be investigated for D2D-enabled NB-IoTs, such as link connectivity, energy limitation of devices, social factors of individuals, and so on . Generally speaking, the following issues need to be well addressed for D2D-enabled information diffusion in NB-IoTs:

- Although D2D communication enables devices to interact directly in LTE networks, existing works mainly focus on reducing multihop transmission delay in D2D-enabled NB-IoT systems. How to guarantee link connectivity has not been fully discussed.
- It is significant to achieve a win-win situation between cellular and D2D users, so that wireless spectrum can be fully utilized by jointly considering social features and network communication constraints in NB-IoTs.
- Different relay methods coexist in NB-IoTs. How to take advantage of the transmission features of D2D communication and cellular network, and integrate the existing relay techniques optimally for fully exploring the wireless spectrum is challenging.
- In order to increase link capacity in NB-IoTs, high-speed content transmission is preferred. However, it is sensitive to network interference and the potential ability for spectrum spatial reuse is limited. Therefore, how to make a tradeoff between transmission rate and spectrum utilization deserves to be investigated.

To cope with the abovementioned issues, we consider the D2D-enabled cooperative uploading, and design a Social-Aware Group formAtion framework (named as SAGA) to allocate RBs effectively for information diffusion following an in-band NB-IoT solution. First, we formulate a general D2D communication model to improve link connectivity and bandwidth following an in-band NB-IoT solution. Then, we present a double auction based social-aware scheme to upload information toward the eNodeB so that a logical cooperative D2D topology among UEs can be established. After that, we formulate an optimization framework to allocate the RBs within a LTE, where the communication links inside can be activated simultaneously. Finally, a novel heuristic method with low computational complexity is proposed to solve the formulated problem approximately. The main contributions of our work can be summarized as follows:

- We develop a cooperative D2D-enabled NB-IoT framework, where D2D communication links can be scheduled by the Base Stations (BSs) in LTE. According to channel state and required transmission rate of cellular links, D2D links within a cell can be stimulated to upload information cooperatively following an in-band NB-IoT solution.
- We present a social-aware relay selection scheme to upload information toward the eNodeB. Driven by gaining extra benefit from network operator, short-range low-power D2D communications are preferred in NB-IoTs. Through encouraging long-range transmissions to be separated into multi-hop D2D transmissions, more opportunities can be created to increase spectrum utilization via cooperative communication in NB-IoTs.
- We define a group formation game to integrate the D2D communications for RB allocation in a cellular network under the constraints of communication cost, transmission power, network load and so on. Our framework can effectively allocate RBs by grouping UEs into a formulation.
- Since the computational complexity of the formulated problem is high, we propose a novel heuristic method to relax the constraints of link scheduling and power control. Based on the synthetic and real trace based simulations, the superiority of our presented optimal method and the effectiveness of our heuristic method can be demonstrated meanwhile.

The remainder of this paper is organized as follows: Section II illustrates the related works, and the system model is stated in Section III. Section IV describes the social-aware group formation framework for information diffusion in NB-IoTs, and a heuristic approximation algorithm is proposed in Section V. Section VI shows the performance evaluations, and some concluding remarks are given in Section VII.

II. Related Works

NB-IoTs can be deployed inside the LTE carrier, so that no additional cost is produced by reusing the 180 KHz bandwidth of LTE physical resource. Since NB-IoT technology is promising for low-power wide-area machine-type communications, this section focuses on the studies from the aspects of information diffusion, spectrum reuse, and network optimization in NB-IoTs.

A. Information Diffusion in NB-IoTs

Due to the widespread deployment of IoT devices, they have become key components to enable information and communication technology developments in smart cities. In order to timely upload information toward the eNodeB, Militano *et al.* allocated short-range D2D chains to lower upload delay [11]. Furthermore, the authors formulated a coalition game to stimulate cooperation among UEs with social selfishness by considering their channel diversity. A context-aware information diffusion scheme for alerting message delivery in 5G was studied in [12], where both the networking and sociality based metrics have been considered for information diffusion time estimation. The context-aware information can be acquired by D2D communications, and the collected data can be integrated and elaborated at the BS before sending out. In [13], Cao *et al.* developed a D2D-enabled social-aware multicast system by taking social trust and social reciprocity into account. The social relationship based group formation is modeled as a coalitional game for video multicasting, and then the authors allocated resource for BS to handle D2D radio resource requests from UEs. Since user selfishness would largely affect the performance of information diffusion in NB-IoTs, Gao *et*

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al. investigated the impact of selfishness in D2D communications [14]. First, two kinds of selfishness transmission patterns are modeled, i.e., connected and opportunistic transmission patterns. Then, a time-varying graph model is designed to study the selfishness impact on D2D communications.

B. Spectrum Reuse in NB-IoTs

Although D2D communication technology is promising to increase spectrum efficiency in cellular networks, how to stimulate resource sharing between cellular and D2D users is challenging. In [15], a social community aware D2D resource allocation framework was investigated to encourage cellular users share channel resource with D2D users in the same community with strong social relationship. A two-step coalition game was further presented to select D2D resource allocation method so that wireless spectrum in the same community can be fully leveraged. Zhang *et al.* studied the Quality of Service (QoS) provisioning for NB-IoTs, and investigated the interplay of resource allocation between macrocells and femtocells [16]. The idea of effective bandwidth is utilized to guarantee UE's QoS. Then the corresponding interplay is formulated into a two-level Stackelberg game. Its objective is to maximize UE's own utility by the joint optimization of macrocell's interference price and femtocell's spectrum utilization. In order to effectively share spectrum resource in NB-IoTs, Wang *et al.* formulated the optimal matching problem of cellular and D2D UEs by increasing sum transmission rates under transmission power and link outage constraints [17]. The authors in [18] utilized graph theory to alleviate the interference between D2D and cellular UEs. The constructed interference graph includes two stages, i.e., the announcement stage and the collision-resolution stage. The former broadcasts the existing D2D links of UEs to their neighboring area, while the latter focuses on handling the generated collisions during the first stage.

C. Joint Optimization in NB-IoTs

In NB-IoTs, transmission data repeation and signal overhead control are viewed promising for network coverage enhancement. An uplink adaptation for NB-IoTs was designed at first, including the adaptations of inner and outer loop links for transmission block error ratio guarantee. By jointly studying the spatiotemporally constraints of coupled link and battery capacity in NB-IoTs, Deng *et al.* decoupled the joint rate and battery control problem into subproblems by dual decomposition [19]. A Stackelberg game based optimization model was formulated to study the interactions between the cellular and D2D users [20]. First, the competition among D2D users is investigated based on non-cooperative game theory. After that, two optimal algorithms are developed for pricing according to the acquired information of BSs. Since the IoT devices with high mobility in the cellular networks challenge the establishment and maintenance of D2D communication links, Alim *et al.* formulated an optimal model for time sensitive content transmission in NB-IoTs [21]. By considering the community based social encounters, the studied method can effectively stimulate D2D communications and reduce the cost of BSs. In order to keep load balancing of D2D communications, a multi-slot online procurement auction framework is formulated as an optimization problem for the sake of minimizing social cost [3]. Then, an online approximation method is presented to solve the formulated NP-hard problem while guaranteeing auction truthfulness.

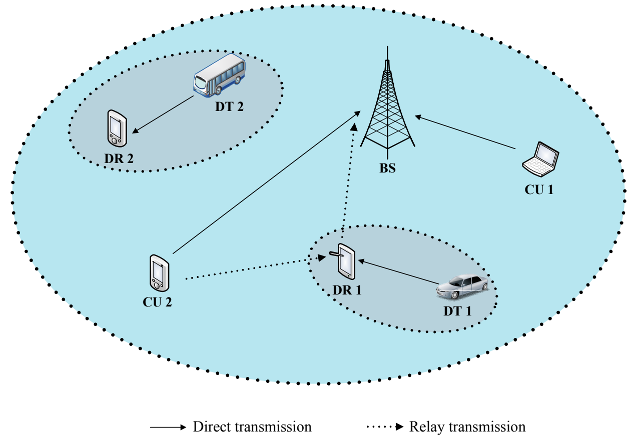

Fig. 1. An illustrative example of D2D communications in LTE networks.

III. System Model

We consider a D2D-enabled OFDMA based LTE network, where multiple devices inside upload content following an in-band NB-IoT solution. As illustrated in Fig. 1, a LTE cell locates in the centre and operates over a licensed spectrum band. Direct D2D communications are possible if the distance of two UEs is within a specific range, and the requirement of Signal-to-Interference-plus-Noise Ratio (SINR) can be satisfied. The considered system can be a small-scale area, such as university campus, shopping center, or transportation junction, where a LTE cell exists for connectivity ensurence. When an emergency accident happens (such as campus violence, fire disaster, or traffic accident), terminal UEs and rescuers should acquire the updated information to handle the corresponding situation. Therefore, the objective of our framework is to provide high link connectivity and capacity by D2D communications, so that the updated information can be diffused effectively and timely in NB-IoTs. We consider a Time Division Multiple Access (TDMA) based scheduler at the eNodeB, which is in charge of allocating the RBs to the scheduled device. If D2D communications are employed, we select UEs that can be stimulated concurrently and grouped together, and utilize various RBs to avoid interference. In the following, we introduce the system backgrounds of LTE and D2D communications respectively. The major notations to be utilized in this paper are shown in Table I.

A. LTE based System Model

In a LTE based system model, the BS (i.e., eNodeB) is in charge of RB allocation before assigning RBs to the scheduled UEs. The network is modelled as a directed graph G=(V, E), where V and E are collections of nodes and links, respectively. Based on the free space propagation loss model, the general received SINR from UEs j' to j by D2D communication can

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TABLE I
THE MAIN VARIABLES AND NOTATIONS USED IN THIS PAPER.

V_i	Set of one-hop nodes of node i.
V_i^+	Set of one-hop outgoing nodes of node i.
V_i^-	Set of one-hop incoming nodes of node i.
$P_{c,j}(P_{i,j})$	Consumed power for cellular (D2D) transmission.
P_i^s	Broadcast power of node i in Configuration s.
$G_{c,j}(G_{i,j})$	Channel gain for cellular (D2D) transmission.
$C_{c,j}$ $(C_{i,j})$	Achievable data rate via cellular (D2D) transmission.
$C_{i,BC}$	Data rate of node i in broadcast transmission.
$\gamma_{i,j}$	SINR value between nodes i and j.
$\Gamma_{C_{i,j}}$	SINR threshold with rate $C_{i,j}$.
φ_i	Social relationship of node i.
$x_{c,j}$ $(x_{i,j})$	Binary variable which is 1 for cellular (D2D) transmission.
φ_j	Social relationship of node j.
$F(C)$	Utility function with data rate C.
$m_i(m_j)$	Markup of source node i (or relay node j).
ω_s	Integer variable which represents the number of time slots for completing transmissions in Configuration s.
PO_i	Payoff of node i.
$U_i(L_i)$	Increased (lost) utility of node i.
u_i^s	Binary variable which is 1 if node i transmits uncoded packets in Configuration s.
c_i^s	Binary variable which is 1 if node i transmits CNC-coded packets in Configuration s.
d_i^s	Binary variable which is 1 if node i transmits DNF-coded packets in Configuration s.

be expressed by:

$$\gamma_{j',j} = \frac{P_{j',j}G_{j',j}}{\eta + \sum_{h \in V-\{j'\}} P_{h,j}G_{h,j}} \geq \Gamma_{Cj',j}, \tag{1}$$

where $P_{j',j}$ and $G_{j',j}$ respectively represent the transmission power and channel gain of node pair $j'-j$. The thermal noise is illustrated by η. V is the group of devices. Since all the devices perform a half-duplex fashion, the concurrent transmitted D2D links may interfere with each other if utilizing the same RB. If the obtained SINR value is above a threshold $\Gamma_{C_{j',j}}$ with transmission rate $C_{j',j}$, it is acceptable for the direct link transmission between j' and j. Otherwise, multi-hop transmission is required to fulfill the transmission task in the direct link.

We also assume all the subcarriers within one RB have the same channel condition as in [12], thus cellular and D2D UEs reuse the same portion of radio spectrum and mutual interference exists. It is noted that the main differences for cellular based and D2D-enabled transmissions concentrate on the transmission power control and interference coordination of concurrent transmission links.

Define C and D as the sets of cellular and D2D UEs respectively, where $C \bigcup D = V$. Let $x_{c,j}$ and $x_{j',j}$ be binary variables to denote whether cellular based or D2D-enabled transmission link is activated (for links from the cellular node to j and from j' to j, respectively). A D2D-enabled session can be constructed if users j' and j can directly interact with each other. Otherwise, an intermediate node i is required to assist the D2D-enabled transmission, and we denote the node group $j'-i-j$ as one session. When we consider a uplink transmission from a cellular user c to the BS (or vice versa), the generated interference by concurrent transmissions to reuse the same RB can be calculated by:

$$I_c = \sum_{j' \in D-\{j\}} x_{c,j} \cdot P_{c,j'} \cdot G_{c,j'} \tag{2}$$

Therefore, the SINR calculation for cellular transmission for the cellular user c is:

$$\gamma_{c,j} = \frac{P_{c,j}G_{c,j}}{\eta + I_c}, \tag{3}$$

and the corresponding achievable data rate (bits per second per Hertz) is $C_{c,j} = Wlog_2(1+\gamma_{c,j})$. Herein, W is the bandwidth of the current RB, and we assume the bandwidth of each link is the same for simplicity.

B. D2D-enabled System Model

Generally speaking, two kinds of D2D communication schemes can be categorized for spectrum resource utilization, i.e., licensed and unlicensed spectrum resources. The former can be further classified into three kinds of modes, i.e., the underlay, overlay and cooperative modes, for reusing the wireless spectrum with cellular users [22]. We first briefly state the underlay and overlay modes for D2D communications. After that, we elaborate the cooperative mode.

1) Underlay and overlay modes: In the underlay D2D communication mode, the UEs of both the cellular and D2D communications simultaneously share the same spectrum band. The main challenge is the management of generated interference between D2D and cellular transmission links. In the overlay D2D communication mode, the transmission rates of cellular links should be satisfied before allocating network resource (channel or RB) to D2D communication links. Although the interference between D2D and cellular links can be decreased by overlay mode, network efficiency of spectrum reuse is lower than that of the underlay mode.

The main concern for the underlay D2D communication mode is to reduce network interference. When a D2D link $j'-j$ is activated for information diffusion, the interference at node j can be computed by:

$$I_j = \sum_{c \in C} x_{c,j} \cdot P_{c,j} \cdot G_{c,j} + \sum_{j' \in D-\{j\}} x_{j',j} \cdot P_{j',j} \cdot G_{j',j} \tag{4}$$

The SINR calculation for underlay D2D transmission from UEs j' to j is:

$$\gamma_{j',j} = \frac{P_{j',j}G_{j',j}}{\eta + I_j}, \tag{5}$$

and the achievable data rate gained by the underlay D2D communication is: $C_{j',j} = Wlog_2(1+\gamma_{j',j})$.

For the overlay mode, a portion of an OFDMA frame is reserved for D2D communication. That is the cellular UEs utilize part of the whole frame length (ξ) for information diffusion, and the D2D UEs leverage the remaining portion. The corresponding transmission rates of cellular based and D2D-enabled links under overlay mode are: $C_{c,j} = \xi Wlog_2(1+\gamma_{c,j})$ and $C_{j',j} = (1-\xi)Wlog_2(1+\gamma_{j',j})$, respectively. It should be noted that interference between cellular and D2D links does not exist under this mode. In order to maximize transmission rate of $C_{j',j}$, ξ can be defined as the portion between the

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required data rate and the maximum achievable data rate of a cellular link. Although the overlay mode does not reuse wireless spectrum effectively compared with the underlay model, it has a smaller overhead over the control channel [23].

2) Cooperative mode: Due to the easy deployment and resource efficient economy, cooperation among terminals plays a critical role in D2D-enabled NB-IoTs. It not only encourages devices with selfish character to forward information for others, but also selects optimal relay method to fully leverage wireless spectrum resource. If the maximum transmission rate of cellular users cannot reach the rate threshold, a relay is necessary. Furthermore, it is a fact that communication between devices can be handled in a multi-hop pattern even there exists a direct path. The reason behind is that high power is necessary for direct transmission with long transmission distance, which brings more interference to other concurrent transmissions. Although the information can be collected and distributed by pervasively deploying sensing, computation, and communication infrastructures, they are costly and energy consuming. In order to reduce the generated interference between cellular and D2D UEs, relay based cooperative transmission is advocated in NB-IoTs.

Generally speaking, the objective of cooperative mode is to maximize D2D user's summation of link capacity under the condition that the data requirement of cellular UEs can be satisfied. Our work concentrates on the design of cooperative D2D communications due to its advantages for NB-IoTs, and we propose a social-aware group formation game to upload information toward the eNodeB following an in-band NB-IoT solution to allocate RB in the following section.

IV. Social-aware Group Formation Game

This section first presents social-oriented metrics to evaluate UE's relationship. Then, a social-aware D2D-enabled relay selection scheme is investigated. After that, an optimal group game is formulated in SAGA to allocate RB in D2D-enabled NB-IoTs.

A. Social-oriented Metrics

The presented social-oriented metrics analyze the information exchanges with surrounding UEs from the aspects of network density, quality and community. The following three aspects of friendships are considered comprehensively.

The Friendship of Neighboring UEs for node j, denoted by FN_j, evaluates the impact degree of UE j with its surrounding UEs during one scheduling cycle. Similar with [24], it is calculated by:

$$FN_j = \frac{1}{|Q_j|} \sum_{j' \in V} \frac{b_{j',j}}{\sum_{h \in V-j} b_{h,j}}, \tag{6}$$

where $b_{j',j}$ is the number of packets to be forwarded from UEs j' to j, and $\sum_{h \in V-j} b_{h,j}$ is the sum of packets from other UEs received by destination UE j. $|Q_j|$ illustrates the amount of neighboring UEs of UE j. It is one type strength that has an influence on other nodes.

The Friendship of Associated UEs for UE j, noted by FA_j, evaluates the friendship between one UE and its associated UEs through the normalization of SINR value over the associated link. Similar with [25], FA_j can be computed by:

$$FA_j = \frac{1}{|A_j|} \sum_{j' \in V} \frac{\gamma_{j',j}}{1+\gamma_{j',j}}, \tag{7}$$

where $|A_j|$ is the number of UEs that j connects with.

The Friendship of Community for j (FC_j) is computed by $\frac{|A_j|}{|V|}$, and $|V|$ is the sum of network UEs. It identifies the quality of UE's friendship within the community. φ_j denotes the social relationship of UE j, and is a weighted value of the three sub-metrics mentioned above.

B. Social-aware D2D-enabled Relay Selection

On one hand, the UEs far from the BS relay their content via other UEs to guarantee network connectivity and increase network throughput. On the other hand, communication between devices can be performed in a multi-hop pattern even a direct path exists to lower transmission power and network interference. If we respectively view the commodity as relay service, the relay and source nodes as seller and buyer, the social-aware D2D-enabled relay selection for NB-IoTs becomes a double auction problem. The auction proceeds periodically, and one-round double auction process is illustrated as follows.

For direct transmission, the corresponding rates for cellular and D2D UEs can be calculated by Shannon equation, i.e., $C_{c,j} = Wlog_2(1+\gamma_{c,j})$ and $C_{j',j} = Wlog_2(1+\gamma_{j',j})$, respectively. If a relay based session is imperative with the assistance of the node i, the required time for fulfilling data transmission is the total transmission time for links $j-i$ and $i-j'$, i.e., $T = \frac{1}{C_{j,i}} + \frac{1}{C_{i,j'}}$. Thus, the relay based transmission rate on link $j-i-j'$ is $C_{j',i,j} = \frac{1}{T} = \frac{C_{j,i}C_{i,j'}}{C_{j,i}+C_{i,j'}}$.

From the viewpoint of the buyer (i.e., source node), the achievable rate promoted by the relay-assisted transmission is: $C_j^i = C_{j,i,j'} - C_{j,j'}$, where C_j^i is the gain that buyer j obtains from seller i. For intermediate nodes (i.e., sellers), they incline to relay for the source nodes under the condition that their resource consumptions can be compensated. We leverage the utility function in [26] to demonstrate the interaction between network utility and transmission rate:

$$F(C) = \alpha(1 - e^{-\beta C}), \tag{8}$$

where α determines the upper bound of the utility function, the curve shape of the function is reflected by β, and C is the achievable link rate.

If packets are forwarded via relay node i from nodes j to j', the increased utility U_j comparing with direct transmission is:

$$U_j = F(C_{j',i,j}) - F(C_{j',j}), \tag{9}$$

where $F(C_{j',i,j})$ and $F(C_{j',j})$ respectively represent the utilities acquired by the relay assisted and direct transmissions.

After offering relay service, the lost ability of relay node i (L_i) in increasing network utility is:

$$L_i = F(C_{i,j}(P_{i,j})) - F(C_{i,j}(P_{i,j} - P_{i,j}^{con})), \tag{10}$$

where $P_{i,j}$ and $(P_{i,j} - P_{i,j}^{con})$ represent the available forwarding ability of relay i before and after packet relay, respectively.

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The consumed power for packet relay is denoted by $P^{con}_{i,j'}$. The available transmission rates before and after relay can be expressed by $C_{i,j'}(P_{i,j'})$ and $C_{i,j'}(P_{i,j'} - P^{con}_{i,j'})$, respectively. $F(C_{i,j'}(P_{i,j'}))$ and $F(C_{i,j'}(P_{i,j'} - P^{con}_{i,j'}))$ are the available utilities before and after packet relay, respectively.

In real market, participants are generally unwilling to reveal the commodity's real value or cost. On one hand, buyer j tends to provide a lower bid than the commodity's real value. On the other hand, seller i inclines to offer a higher ask than its real cost. The mark-up deviated from the actual value is defined as the extra part in economic terminology. Correspondingly, the bid and ask of the source UE j and relay UE i are:

$$U^{bid}_j = U_j(1 - m_j), \tag{11}$$

$$L^{ask}_i = L_i(1 + m_i), \tag{12}$$

where $m_j \in [0, 1]$ and $m_i \in [0, 1]$ are the mark-ups of buyer j and seller i, respectively.

The authors in [27] assumed the mark-up of all the nodes is the same, while the mark-up in our work varies according to node social relationship and residual energy in NB-IoTs. The reasons are two-fold: 1) UEs with socially selfish character prefer to relay messages for those with strong social relationship; 2) the source UE would not incline to buy the relay service if its residual resource is plenty. Under these two circumstances, the source UE would bid a relative low price. Otherwise, it prefers to provide a truthful bid to acquire transaction opportunities. The mark-up of the source node is:

$$m_j = \zeta_j \varphi_j + (1 - \zeta_j)\frac{AE_j}{TE_j}, \tag{13}$$

where ζ_j is the weighting factor of node $j's$ social relationship, and φ_j is the social relationship factor of UE j. AE_j and TE_j respectively illustrate the available (residual) energy and total energy of UE j.

For the relay UE, the corresponding mark-up calculation is diverse. For one thing, the seller is unwilling to provide service for other UEs if its residual energy is not sufficient. This is because its communication task should be fulfilled before gaining extra profit. Besides, the source UE with strong social relationship is possible to obtain more relay services by bidding. On these occasions, a high price is asked, and the corresponding mark-up is:

$$m_i = \zeta_i \varphi_i + (1 - \zeta_i)(1 - \frac{AE_i}{TE_i}), \tag{14}$$

where the variables in (14) are defined similarly with (13).

A single cell in the LTE network is considered in our work, where multiple UEs intend to upload their content toward the eNodeB. Different from the traditional cellular mode transmission, UEs with pool link state can upload content toward the eNodeB UEs in reciprocal proximity by forming groups in a D2D-enabled cooperative NB-IoT mode. Under the control of the eNodeB, UEs within a group can form a logical multi-hop D2D chain to upload content. We assume a central bank model, and each UE's account is recorded in the network system. The access channel contains control and data subchannels. The subchannel includes the information of channel condition and central bank. After the content of source UE has been delivered with success, virtual money is transferred to the relay UE from the central bank, and the winning relay UE will receive the corresponding virtual money through the the central bank.

The PayOff (PO) for the winning out source node j is:

$$PO_j = U_j - Pay_j. \tag{15}$$

where Pay_j is node j's actual payment.

Similarly, the payoff for the winning out intermediate node i is:

$$PO_i = Rec_i - L_i. \tag{16}$$

where Rec_i is the actual reception of node i.

We assume that the economic profit of the central bank is 0 during the double auction. According to the economic theory in [28], the payment Pay_j and reception Rec_i equal to:

$$Pay_j = Rec_i = \frac{U^{bid}_j + L^{ask}_i}{2} \tag{17}$$

UE's virtual money in the central bank varies according to (15) and (16) after one-round double auction process terminates. It is demonstrated in **Appendix A** that our method can approach a win-win situation for both seller and buyer.

Our presented double-auction based game model can achieve an equilibrium. This is because the achievable transmission rates of source nodes are strictly convex and continuous, and the gained profits of our game are non-negative. Furthermore, for the n-player normal form game, at least one Nash equilibrium point exists if both the amonunts of player and the strategy are finite, some existing schemes (such as [29], [30]) can be employed to obtain the Nash equilibrium in our formulated game.

C. An Optimized Group Formation Game

The transmission rate of cellular UE has a minimum requirement, while the counterpart in D2D communications does not have. Similar with [22], we also focus on the situation that uplink cellular links share the spectrum with D2D communication links, and the investigated model can be also generalized to downlink cellular links for RB allocation. Before describing the details of the optimized group formation game, we first illustrate the main principles for spectrum allocation between cellular and D2D communication links, i.e.,

- Each cellular link is allocated to one configuration, and each D2D communication link is assigned to no more than one configuration.
- If the required transmission rate of cellular link can be satisfied, D2D communication links can share with the spectrum occupied by the cellular link.
- If the cellular link transmission is fulfilled via the assistant of D2D communication terminals, it can obtain reward from the BS directly.

For the sake of decreasing interference between the cellular and D2D links, D2D links within close proximity to the cellular links are identified to guarantee that they do not reuse the same RBs. For multihop D2D communications, it

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is essential to reduce the generated interference by concurrent transmissions within the same RB. After performing the social-aware D2D-enabled relay selection in Section IV.B, long-range transmission links can be substituted by short-range multi-hop transmissions, so that devices can communicate with each other in a small-world network with strong relationship.

In order to fully leverage wireless spectrum, this subsection presents an optimized group formation game so that different relay methods, including Physical-layer Network Coding (PNC), Conventional Network Coding (CNC), space-division multiple access, and plain routing, can be integrated in an optimal way to form a group for RB allocation, where D2D communication links inside can be activated simultaneously. Details for the illustration of the corresponding relay methods can refer to [31]. We focus on the DeNoise and Forward (DNF) scheme of PNC since it can well resist noise.

We define S as the configuration of formulated link groups, and denote an integer variable ω_s to illustrate the required number of time slots for activating a specific configuration $s \in S$. Unicast, CNC and DNF based transmissions are represented by the binary variables u_i^s, c_i^s and d_i^s, respectively. For a relay node i, V_i is a collection of relay node i's associated nodes. If node $j \in V_i^-$ or $j \in V_i^+$, it is an incoming or outgoing node of relay node i, respectively. The optimal group formation game within one scheduling period can be modeled as follows.

$$\min \sum_{s \in S} \omega_s \tag{18}$$

subject to:

$$x_{i,j}^s + x_{j,i}^s \leq 1 \tag{19}$$

$$u_i^s + c_i^s + d_i^s \leq 1 \tag{20}$$

$$\sum_{j \in V-\{i\}} x_{i,j}^s \leq 1 + (1 - u_i^s) \tag{21}$$

$$\begin{aligned} \sum_{s \in S} (u_i^s + c_i^s + d_i^s) x_{i,j}^s \omega_s W_{i,j}^s \geq \; & u_i^s Y_i^j + \\ d_i^s \sum_{j' \in V_i^- - \{j\}} Y_i^{j,j'} + (c_i^s + d_i^s) & \sum_{j' \in V_i^+ - \{j\}} Y_i^{j,j'} \end{aligned} \tag{22}$$

The objective of the group formation game is to maximize the achievable network throughput within one RB in NB-IoTs, and it is equivalent to minimize the totally required activating time $\sum_{s \in S} \omega_s$ by the comprehensive selection of relay method. Constraint (19) is the half-duplex requirement, i.e., any node cannot simultaneously receive and transmit packets. Constraint (20) illustrates merely one transmission pattern can be selected by relay node i within one scheduling period. If the unicast mode is determined by node i, Constraint (21) guarantees no more than one link can be stimulated within one scheduling period.

Constraint (22) demonstrates that transmission links deserve to be activated long enough so that all the transmission tasks can be accomplished. In (22), $W_{i,j}^s$ indicates the number of transmission packets on link $i \rightarrow j$ within one scheduling period. Y_i^j represents the number of unicast traffic via node i on link $i \rightarrow j$. For the multiple access phase of DNF, traffic amount transmitted by links $j \rightarrow i$ and $j' \rightarrow i$ can be illustrated by $\sum_{j' \in V_i^- - \{j\}} Y_i^{j,j'}$. For the broadcast process of CNC and DNF, the broadcasted traffic via node i on links $i \rightarrow j$ and $i \rightarrow j'$ can be illustrated by $\sum_{j' \in V_i^+ - \{j\}} Y_i^{j,j'}$.

Constraints (23) to (27) are employed for transmission mode selection of relay node i. In (23), it means if over one outgoing flow is from node i, either CNC or DNF method is selected. Constraint (24) means DNF method would be chosen if over one incoming flow is to node i. However, if merely one incoming flow ($u_i^s = 1$ or $c_i^s = 1$) to node i exists, d_i^s should be 0 as shown in (25). The maximum amount of incoming links is limited to 2 if DNF is selected for decodability ensurance as illustrated in (26). Constraint (27) means over one outgoing link exists if the coded packets ($c_i^s = 1$ or $d_i^s = 1$) are broadcasted by the relay node.

$$c_i^s + d_i^s \geq \sum_{j \in V_i^+} x_{i,j}^s - 1 \tag{23}$$

$$d_i^s \geq \sum_{j \in V_i^-} x_{i,j}^s - 1 \tag{24}$$

$$d_i^s \leq \sum_{j \in V_i^-} x_{i,j}^s - u_i^s - c_i^s \tag{25}$$

$$\sum_{j \in V_i^-} x_{i,j}^s \leq 1 + d_i^s \tag{26}$$

$$1 + \sum_{j' \in V_i^+ - \{j\}} x_{i,j'}^s \geq x_{i,j}^s + c_i^s + d_i^s \tag{27}$$

Next, we investigate the power constraint of different transmission methods. For unicast transmission, the SINR constraint is shown as:

$$\begin{aligned} P_{j,j'} G_{j,j'} + M_{j,j'}^s (1 - x_{j,j'}^s) + M_{j,j'}^s (1 - u_j^s) \geq \Gamma C_{j,j'} [\eta + \\ \sum_{h \in V-\{j\}} P_{h,j'} G_{h,j'} u_h^s + \sum_{h \in V-\{j\}} P_{h,BC} G_{h,j'} (c_h^s + d_h^s)] \end{aligned} \tag{28}$$

In (28), $P_{h,BC}$ represents the broadcast power on node h for CNC or DNF. In order to ensure the decodability of the destination nodes, the maximum power of $P_{i,j}$ and $P_{i,j'}$ should be selected as the broadcast power of relay node i ($P_{i,BC}$). $M_{j,j'}^s$ is a constant value, which equals to the summation of the right-side in (28). It guarantees the limitation of the cumulative interference (generated by other concurrent transmission links) on destination node is below a threshold.

In the multiple access process of DNF, we employ the minimum received power ($\min(P_{j,i} G_{j,i}, P_{j',i} G_{j',i})$) for SINR computation, and assume $P_{j,i} G_{j,i} < P_{j',i} G_{j',i}$ without loss of generality, the SINR constraint of multiple access in DNF can be shown as:

$$\begin{aligned} P_{j,i} G_{j,i} + M_{j,i}^s (1 - x_{j,i}^s) + M_{j,i}^s (1 - d_j^s) \geq \Gamma_{Cj,i} [\eta + \\ \sum_{h \in V-\{j\}} P_{h,i} G_{h,i} u_h^s + \sum_{h \in V-\{j\}} P_{h,BC} G_{h,i} (c_h^s + d_h^s)] \end{aligned} \tag{29}$$

where $M_{j,i}^s$ is no less than the right part of (29).

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The SINR constraint of node j for the broadcast process of CNC and DNF methods can be demonstrated as:

$$P_{i,BC}G_{i,j} + M_{i,j}^s(1-x_{i,j}^s) + M_{i,j}^s(1-c_i^s-d_i^s) \geq \Gamma_{C_{i,j}}[\eta + \sum_{h\in V-\{i\}} P_{h,j}G_{h,j}u_h^s + \sum_{h\in V-\{i\}} P_{h,BC}G_{h,j}(c_h^s+d_h^s)], \tag{30}$$

Thus, one schedule S within a RB contains such a collection of current configurations, i.e., $s \in S$, which can be identified by binary variables $x_{i,j}^s, u_i^s, c_i^s, d_i^s$, and transmission power. By Constraints (23) to (30), we can make sure the corresponding available relay method. Then, by Constraints (19) to (22), the minimum activation time slot can be calculated. However, the corresponding link scheduling problem with fixed transmission rate has been acknowledged as a NP-complete problem [32]. In the next section, we propose a joint power control and relay selection heuristic to lower the computational complexity for group formation to allocate RB.

V. A Joint Power Control and Relay Selection Heuristic for Group Formation

We can observe that the high computational complexity of our formulated Integer Linear Programming (ILP) problem mainly comes from two parts, i.e., relay method selection and transmission power allocation. We notice that the formulated optimization problem can be solved approximately by some existing methods in polynomial time if the transmission rate can be fixed by power control. However, the number of link combinations with various transmission power is huge, not to mention the selection of different relay methods by link scheduling. In this section, we present a joint Power cOntrol and Relay Selection heuristic (named as PORS), which consists of the following four procedures:

- Prune edges: we first remove some extra-essential link edges from graph G to reduce link searching space.
- Relaxation of the formulated ILP problem.
- Power control: we then regulate transmission power to join concurrent transmission links into the configuration iteratively.
- Link combination selection: we propose a heuristic method to select link allocation combinations by jointly considering various communication factors.

A. Prune Edges

Generally speaking, UEs forward information to their near-by neighbors with high rate, while to the farther neighbors with low rate. Thus, a large number of potential paths with various transmission rates exist between the source and destination nodes. Since the computational complexity of the group formation increases sharply as the number of edges adds. In the first step, we compute the k-shortest paths between one node and the other communication nodes according to Yen's algorithm [33]. Similar with [34], we set link cost as the reciprocal of the maximum possible transmission link. It is obvious that the selection of parameter k makes a tradeoff between computational speed and obtained network performance.

B. Problem Relaxation

We relax the integer constraint of ω_s to real value ν_s, and start to solve the formulated problem preliminary with $S_0 \in S$. The objective of the relaxed optimization problem becomes:

$$\min \sum_{s\in S_0} \nu_s \tag{31}$$

subject to:

$$\sum_{s\in S_0}(u_i^s+c_i^s+d_i^s)x_{i,j}^s\nu_s W_{i,j}^s \geq u_i^s Y_i^j + d_i^s \sum_{j'\in V_i^- -\{j\}} Y_i^{j,j'} + (c_i^s+d_i^s)\sum_{j'\in V_i^+ -\{j\}} Y_i^{j,j'} \tag{32}$$

The relaxed master problem in (32) can be solved by Linear Programming (LP), and we can obtain a preliminary optimal solution. After that, ν_s is restricted to an integer variable in the LP problem. If the optimal solution can be found, the problem relaxation process terminates. Otherwise, the current gained value is a lower bound of the optimal solution, and we start to solve the slave problem.

Denote ϑ as the dual variable of ν_s in (32), the reduced cost can be computed by $(1 - x_{i,j}^s\vartheta_{i,j}^s)$ according to the LP theory [35]. In order to minimize ν_s in the master problem, the value of $x_{i,j}^s\vartheta_{i,j}^s$ should be maximized in the slave problem, i.e., $(1-x_{i,j}^s\vartheta_{i,j}^s)$ should be minimized. Therefore, during each iteration, $\vartheta_{i,j}^s$, with the most negative value of $(1-x_{i,j}^s\vartheta_{i,j}^s)$, is selected. If the reduced cost cannot be less than 0, the iteration terminates. Since the current slave problem still has binary and continuous variables, the next subsection presents a distributed power control method to reduce the computation complexity further.

C. Power Control

In order to relax power constraints in (28)-(30), we propose a distributed power control based scheme to select the D2D-enabled concurrent transmission links. On one hand, the link with large transmission power can obtain a high rate. On the other hand, large transmission power brings high interference to others and limits the concurrent transmissions of neighboring nodes. In order to increase link capacity in NB-IoTs, how to make a tradeoff between the number of concurrent transmission links and the achievable link rates deserves to be studied.

A straightforward way to balance transmission rate and spatial reuse is to control the transmission power, so that the interference range can be limited to a special area. Our core concept is to join links into the configuration iteratively, so that the interference among concurrent transmission links can be controlled. If the SINR constraint cannot be satisfied, the corresponding link cannot join into the configuration.

At beginning, the initial link set in Configuration s is null. With the objective of decreasing interference, the links are selected to join into the configuration from the one with the best channel state. For one link, the channel state can be reflected by two factors, i.e., achievable SINR value and the ability of interference resistance. Interference range illustrates

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the distance, within which the SINR threshold can be reached for the transmission link when other interference links also exist. Obviously, a larger SINR value accompanies with a longer interference range, and it is tolerant to more interference caused by concurrent transmission links. We define the link selection criteria as follows:

$$l_{i,j} \rightarrow \arg\{\max_{i,j\in V}(\frac{\Gamma_{C_{i,j}} G_{i,j}}{\sum_{h\in V-\{i\}} G_{h,j}})\}, \tag{33}$$

When the first activated link is determined, the minimum required transmission power is:

$$P_{i,j} \geq \frac{\Gamma_{C_{i,j}}\eta}{G_{i,j}} \tag{34}$$

After that, we continue to add other links into the configuration. According to link selection criteria, if another link $l_{m,n}$ is supplemented into Configuration s with transmission power $P^s_{m,n}$, the corresponding interference generated by the newly added link is:

$$\Delta I_j \geq P^s_{m,n} G_{m,j} \tag{35}$$

To avoid the interruption of the current transmission links after new links are joined into Configuration s, the transmission power should be increased by at least:

$$\Delta P_{i,j} = \frac{\Delta I_j \Gamma_{C_{i,j}}}{G_{i,j}} \geq \frac{P_{m,n} G_{m,j} \Gamma_{C_{i,j}}}{G_{i,j}} \tag{36}$$

which sets a threshold on $P^s_{m,n}$, i.e.,

$$P_{m,n} \leq \frac{\Delta P_{i,j} G_{i,j}}{G_{m,j}\Gamma_{C_{i,j}}} = \frac{(P_{max} - P_{i,j})G_{i,j}}{G_{m,j}\Gamma_{C_{i,j}}} \tag{37}$$

The link selection problem can be transferred as maximizing the SINR value at the destination node, i.e.,

$$l_{i,j} \rightarrow \arg\{\max_{m,n\in V-\{i,j\}}\{\min_{i,j\in V}\frac{(P_{max} - P_{i,j})G_{i,j}}{G_{m,j}\Gamma_{C_{i,j}} I_j}\}\} \tag{38}$$

The iteration of supplementing unicast links into the configuration continues until the transmission power of the newly joined link exceeds P_{max} or no more links need to be activated. Since our presented PORS is distributed, the high computational complexity in Constraints (28)-(30) can be largely decreased. After this subsection, one configuration with multiple interference-free unicast links can be generated for current transmission within one RB.

D. Link Combination Selection

With the objective of increasing link capacity in NB-IoTs, utilizing all the possible coding opportunities at the relay node is not always effective. Instead, how to consider the interplay among different relay methods and select the proper set of packets for coding deserves to be investigated. In this subsection, we study a link combination selection scheme by considering different communication factors for RB allocation.

The information of coding opportunity, network cost, packet size, channel condition and etc. has impact on the performance of group formation. Although the optimal solution can be obtained by checking all the group formations, it is time consuming on one hand; On the other hand, the coding opportunity of some packets in CNC and DNF may not be overheard successfully, which would lower the overall throughput. Therefore, it is not always the best choice to encode as many packets as possible.

For one scheduled node, the most important component is to decide the combination of concurrent transmission links with different relay method. First, the relay node checks all the possible link combinations of the corresponding schedule task. Then, we utilize the information of link rate, coding opportunity, overhead and packet size to determine the suitable combination of link transmissions, so that link capacity can be increased by RB allocation in NB-IoTs. Due to the high computational complexity of the formulated optimization problem in Section IV.C, a heuristic solution is leveraged to handle this issue. We define Ω^s_i as the sum achievable link rate by link combination, and the target of the optimal group formation game becomes:

$$\min \sum_{s\in S}\sum_{i\in V}\Omega^s_i \tag{39}$$

where

$$\Omega^s_i = \begin{cases} c^s_i \times C_{i,BC} \times \dfrac{2n^C_i}{2n^C_i - 1} \times \dfrac{n^C_i \times L}{n^C_i \times L_C + L},\ if\ CNC \\ d^s_i \times C_{i,BC} \times \dfrac{n^D_i}{n^D_i - 1} \times \dfrac{n^D_i \times L}{n^D_i \times L_D + L},\ if\ DNF \\ u^s_i \times C_{i,j} \times \phi,\ Others \end{cases} \tag{40}$$

In (40), the corresponding transmission rates for broadcast and unicast are $C_{i,BC}$ and $C_{i,j}$, respectively. For decodability, the broadcast power should be the maximum one among all the unicast transmission power. $\frac{2n^C_i}{2n^C_i-1}$ and $\frac{n^D_i}{n^D_i-1}$ are the gains respectively achieved by CNC and DNF [36]. The number of nodes selected for conducting CNC and DNF is illustrated by n^C_i and n^D_i, respectively. The number of concurrent activated links is denoted by ϕ, and unicast transmission corresponds to ϕ=1. L_C and L_D are extra header costs for the implementation of CNC and DNF, respectively. Packet size is denoted by L. The combination of the three component in (40) illustrates the achievable transmission rate in Configuration s. Our presented metric is different from the solution in [37], which only focuses on the number of coding pairs in CNC. Instead, we take coding opportunity. network cost in CNC and DNF, multi-rate transmission, and spatial reuse into consideration.

After Section V.A, we can eliminate some trivial links in the network graph to increase searching ability. Section V.B relaxes the formulated ILP problem in Section IV.C. In Section V.C, we can transform the joint power and rate control problem to a fixed link rate allocation problem. Then, Section V.D uses an opportunistic link combination scheme to solve the group formulation problem for RB allocation.

VI. Performance Evaluation

Before providing performance analysis in this section, we illustrate the experiment setup first, which consists of the setups of synthetic simulation and real trace based simulation.

For synthetic simulation setup, up to 50 nodes are randomly distributed over a 500m×500m area within a single cell.

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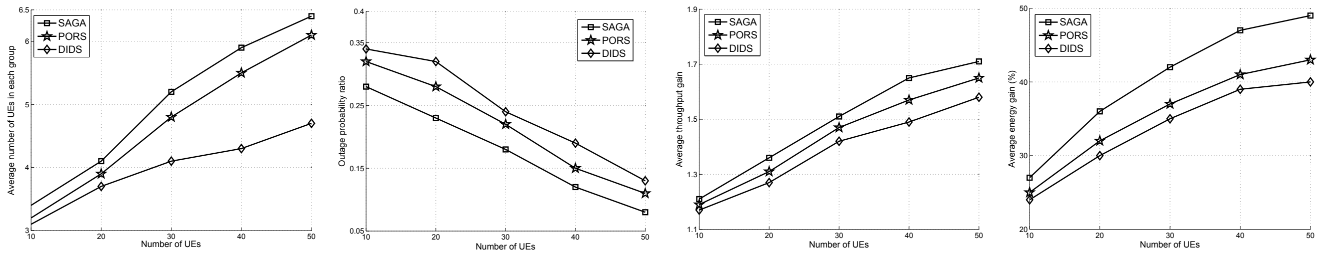
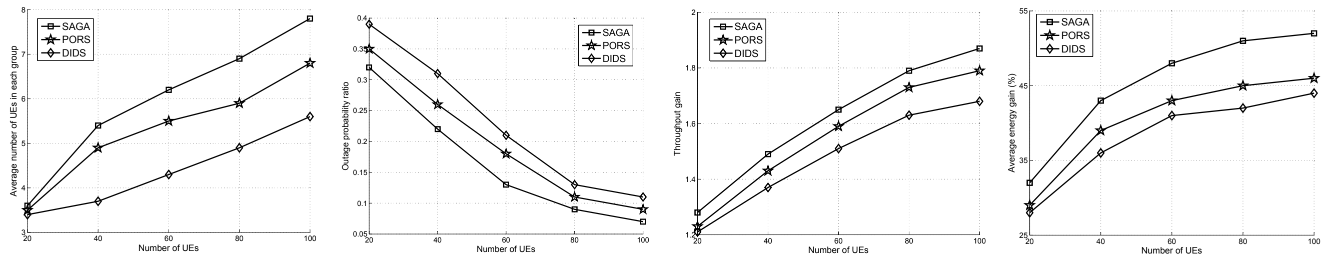


(a) Number of UEs in each group (b) Outage probability ratio (c) Throughput gain (d) Energy gain

Fig. 2. Performance comparisons in synthetic based simulations.



(a) Number of UEs in each group (b) Outage probability ratio (c) Throughput gain (d) Energy gain

Fig. 3. Performance comparisons in real trace based simulations.

Data requests are generated uniformly between 6 and 10 Kbits. The maximum coverage regions for cellular and D2D communications are 500m and 100m, respectively. Specifically, we consider an urban microcell circumstance based wireless transmission model in WINNER II channel models [38]. We set the weighting factors of the three social-oriented submetrics equal to $\frac{1}{3}$, and carrier frequency equal to 2.1 GHz. In our simulation, $\alpha = 1$, $\beta = \frac{\ln(0.1)}{12.5}$, and $\eta = 10^{-6}$ mW according to [26].

For real trace based simulation setup, we use SIGCOMM09 data set [39] for performance evaluation. It includes the information of social and contact among 100 UEs generated by cell phones, and users log onto Facebook to obtain their interests and profiles. By the analysis of contact records among UEs, we can acquire the corresponding information of physical proximity.

In order to demonstrate the superority of our SAGA, we consider both the heuristic method PORS and the D2D-enhanced Information Diffusion Scheme in [12] (we call it DIDS for convenience), and evaluate the following four performance indexes:

- Average number of UEs in each group, which illustrates the average number of UEs in a multihop D2D chain within a group.
- Outage probability ratio, which is the ratio of link transmission that cannot satisfy the rate requirement among all the intended transmission links.
- Average throughput gain, which is the ratio between the required time slots by merely employing cellular scheduling and the counterpart by leveraging the studied group formation game.
- Average energy gain, which illustrates the percent of energy saving by implementing the designed group formation game comparing with cellular uploading only.

Figs. 2(a) and 3(a) demonstrate the average number of UEs in each group in both synthetic and real trace based simulations. We can observe that the number of UEs within each group increases as the number of UEs adds in the cell, which means UEs have more opportunities to be formulated into one group for current transmission. Both SAGA and PORS outperform DIDS, especially when the number of UE is large. This is mainly because our method jointly considers the interplay among different relay methods in D2D-enabled communications, which can activate more concurrent transmission links and have a better utilization of spectrum reuse. Besides, DIDS focuses on minimizing the diffusion time of content transmission for emergency circumstance, while our solution concentrates on RB allocation in D2D-based NB-IoTs. Furthermore, since the searching space of the heuristic algorithms (i.e. PORS and DIDS) is limited, the performance gap between SAGA and them enlarges as the number of UEs increases.

Performances of average outage probability ratio vs. the number of UEs are shown in Figs. 2(b) and 3(b). As the number of UEs increases, these three schemes can reduce link outage probabilities significantly by D2D-enabled cooperative transmission. Both SAGA and PORS have lower outage probabilities than DIDS, which shows the effectiveness of our presented incentive group formation for RB allocation. Because a win-win situation can be gained by our method, more intermediate UEs are inclined to participate in the double-auction game, so that more opportunities can be found for packet forwarding. Thus, the outage probability can be largely decreased.

In Figs. 2(c) and 3(c), we can observe that the achieved average network throughput gain by SAGA is around 10% higher than that in DIDS. Although both networking and sociality based metrics have been considered in DIDS, our

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method not only considers various relay methods, but also studies the interplay among transmission rate and interference. We note that PORS can approach the performance gained by SAGA effectively with low computational complexity, the minor degradation mainly comes from the searching space reduction, and the relaxtion of relay method selection and transmission power.

The performances of energy gain obtained by different number of UEs have been illustrated in Figs. 2(d) and 3(d). It is obvious that by both D2D and relay based communications, the obtained energy gains increase constantly. It is noted that, at the beginning, the increase of energy gain keeps almost linear as the number of UEs enhances. When the amount of UEs adds up to a certain degree, there are plenty of opportunities for source and relay nodes selection in the double auction game, and the curves become stable. Since our method encourages long-term transmission links to be conveyed by multi-hop short range transmissions, it can effectively avoid long-range transmissions and strong interference among UEs, so that high energy gain can be obtained.

VII. Conclusion

The implementation of NB-IoT is still in its infancy, how to guarantee link connectivity and provide high link capacity is challenging. In this paper, we first present a D2D-enabled communication framework for NB-IoTs by encouraging UEs to upload information with a cooperative manner. Then, we propose a social-aware D2D-enabled relay selection method for information uploading to the eNodeB. After that, we study a group formation game to activate concurrent transmission links for RB allocation. Since the computational complexity of the formulated problem is rather high, we propose a novel heuristic scheme to solve the studied problem iteratively by comprehensively investigating the interplay between transmission rate and relay method, and relaxing the constraints of link scheduling and power control. Performance evaluations based on both synthetic and real trace simulation results illustrate the superiority of our present scheme in group efficiency, outage probability, throughput gain and energy efficiency.

VIII. Acknowledgement

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Appendix A

Theorem 1: The double auction based scheme proceeds until the gained profits by the source and relay nodes are negative, which should satisfy: $U_j^{bid} \geq L_i^{ask}$.

Proof: Since $U_j^{bid} \geq L_i^{ask}$ according to (11) and (12), it is obvious that:

$$U_j(1-m_j) \geq L_i(1+m_i), \tag{41}$$

Thus, we can get the result that:

$$U_j - L_i \geq U_j \times m_j + L_i \times m_i, \tag{42}$$

According to (11), (12) and (17), we can find that:

$$\begin{aligned} Pay_j &= U_j - \frac{U_j^{bid} + L_i^{ask}}{2} \\ &= U_j - \frac{U_j(1-m_j) \geq L_i(1+m_i)}{2} \\ &= \frac{U_j - L_i + U_j \times m_j - L_i \times m_i}{2} \end{aligned} \tag{43}$$

According to (33), we can obtain that:

$$\begin{aligned} Pay_j &= \frac{U_j - L_i + U_j \times m_j - L_i \times m_i}{2} \\ &\geq \frac{U_j \times m_j + L_i \times m_i + U_j \times m_j - L_i \times m_i}{2} \\ &= U_j \times m_j \geq 0. \end{aligned} \tag{44}$$

Similarly, the conclusion is:

$$Rec_i \geq I_i \times m_i \geq 0. \tag{45}$$

Thus, a win-win situation can be achieved by our method.

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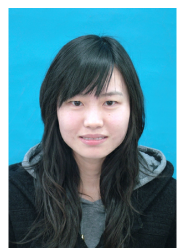

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